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Efficient Modelling Methodology for Reconfigurable Underwater Robots

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Abstract: This paper considers the challenge of applying reconfigurable robots in an underwater environment. The main result presented is the development of a model for a system comprised of N, possibly heterogeneous, robots dynamically connected to each other and moving with 6 Degrees of Freedom (DOF). This paper presents an application of the Udwadia-Kalaba Equation for modelling the Reconfigurable Underwater Robots. The constraints developed to enforce the rigid connection between robots in the system is derived through restrictions on relative distances and orientations. To avoid singularities in the orientation and, thereby, allow the robots to undertake any relative configuration the attitude is represented by quaternions.

Keywords: Udwadia-Kalaba, Multi-body Dynamics, Quaternion, Autonomous Underwater Vehicles, Reconfigurable Robots

1. INTRODUCTION

The offshore industry is becoming technologically ever more demanding and visions foresee production facilities will move from the ocean surface to the seabed. Consequently, robotic solutions will have to solve increasingly diverse tasks and collaborating and reconfigurable robots are envisaged to become important in support of this technology evolution. This paper deals with modelling for control of multi-robot systems with an aim of being able to automate the modelling of vehicles that should be able to connect or disconnect and form configurations required for a specific task. The modelling should be able to be done without human intervention other that the definition of dynamics for the individual vehicle.

Present solutions focus on Remotely Operated Vehicles (ROVs) for power demanding tasks such as positioning of subsea modules during the installation phase Henriksen et al. (2015). Several low-power tasks are, however, better carried out by non-tethered vehicles, and in the long term a modular reconfigurable multi-robot solution can provide high control authority and flexibility. This means that several autonomous vehicles work together to perform a joint task. Multi-vehicle systems for underwater applications were studied in Belleter and Pettersen (2014, 2015) where formation control was the main objective. The focus in this paper is modular reconfigurable multi-robot system that is capable of physically changing its morphology. From a reconfiguration point-of-view work has mainly focused on modularity in the physical sense. An underwater platform with docking capability to offload data between a sensor network and an Autonomous Underwater Vehicle (AUV) was presented in Vasilescu et al. (2005), and Mintchev et al. (2012, 2014) presented a system of anguilliform AUVs with the ability of docking to each other, utilising passive magnets to align the vehicles for docking. The system resulting from physically coupling and de-coupling of the vehicles is a multi-body system with dynamic topology. The modular robotics community predominantly focus on Fuzzy Logic control of multi-body systems, but when high precision control is needed, modelling is a necessary prerequisite. Generic modelling for individual underwater vehicles has been extensively treated in Antonelli (2014) and Fossen (2011), so the challenge for a multi-body cluster is to be able to describe the non-linear dynamics of the cluster from the dynamics of individual members.

The objective of the present effort is hence to provide a modelling tool that can describe the dynamic properties of a morphology from the geometry of the cluster and properties of its' members. The challenge with traditional modelling methods is the difficulties that arise from constraints when robots connect. The paper develops the equations of motion for a system comprised of N rigidly connected robots based on the Udwadia-Kalaba Formulation (Udwadia and Schutte, 2012). We exploit this framework using quasi-velocities to derive the constraints imposed by rigid connections, using a quaternion formulation to avoid singularities. The contribution of the paper is to show how the Udwadia-Kalaba methodology can be applied to reconfigurable underwater robots, and in particular can deal with redundant constraints in a robust manner.

The paper first lists the notation along with the kinematics and kinetics needed. Section 3 discusses the general

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problem of constrained dynamics and Section 4 shown how the Udwadia-Kalaba approach can be applied to handle the constraints of a generic morphology of connected underwater robots. Finally, a series of simulations verify the automated modelling concept, and Section 7 provides conclusions and perspectives.

2. RIGID-BODY MODEL

2.1 Notation and Kinematics

This section summarises the notation broadly used in the area of underwater vehicles, as this was introduced in Fossen (2011). For the purpose of this paper the earth-fixed North-East-Down (NED) frame, denoted $\{n\}$, will be assumed inertial. The frame configuration variables denoted $\boldsymbol{\eta} = [\boldsymbol{p}^n_{b/n}, \boldsymbol{u}]^T \in \mathbb{R}^7$ comprise of the position $\boldsymbol{p}^n_{b/n} = [x^n, y^n, z^n]^T$ and the attitude represented as a unit quaternion to avoid singularities $\boldsymbol{u} = [\eta, \varepsilon_1, \varepsilon_2, \varepsilon_3]^T$. Attached to each body in the system is a local body-fixed frame denoted $\{b\}$. The body-fixed velocities denoted $\boldsymbol{\nu}$ as

$$\boldsymbol{\nu} = [u\ v\ w\ p\ q\ r]^T \in \mathbb{R}^6 \tag{1}$$

As with the configuration vector the body-fixed velocity vector can be separated into linear velocities $\boldsymbol{\nu}_1 = [u, v, w]^T$ and angular velocities $\boldsymbol{\nu}_2 = [p, q, r]^T$. To relate the NED and body-fixed frame the rotation matrix $\boldsymbol{R}^n_b$ defined below

$$\boldsymbol{R}^n_b = \begin{bmatrix} 1-2\left(\varepsilon_2^2+\varepsilon_3^2\right) & 2\left(\varepsilon_1\varepsilon_2-\varepsilon_3\eta\right) & 2\left(\varepsilon_1\varepsilon_3+\varepsilon_2\eta\right) \\ 2\left(\varepsilon_1\varepsilon_2+\varepsilon_3\eta\right) & 1-2\left(\varepsilon_1^2+\varepsilon_3^2\right) & 2\left(\varepsilon_2\varepsilon_3-\varepsilon_1\eta\right) \\ 2\left(\varepsilon_1\varepsilon_3-\varepsilon_2\eta\right) & 2\left(\varepsilon_2\varepsilon_3+\varepsilon_1\eta\right) & 1-2\left(\varepsilon_1^2+\varepsilon_2^2\right) \end{bmatrix} \tag{2}$$

To relate the attitude change in the inertial frame $\{n\}$ with the angular velocities $\boldsymbol{\omega}^b_{b/n}$ around the principle axes of the body-fixed frame $\{b\}$ the angular transformation matrix $\boldsymbol{T}_u$ is used.

$$\dot{\boldsymbol{u}} = \boldsymbol{T}_u \boldsymbol{\omega}^b_{b/n} \tag{3}$$

where $\boldsymbol{T}_u$ is defined as

$$\boldsymbol{T}_u = \frac{1}{2}\boldsymbol{H}^T = \frac{1}{2}\begin{bmatrix} -\varepsilon_1 & -\varepsilon_2 & -\varepsilon_3 \\ \eta & -\varepsilon_3 & \varepsilon_2 \\ \varepsilon_3 & \eta & -\varepsilon_1 \\ -\varepsilon_2 & \varepsilon_1 & \eta \end{bmatrix} \tag{4}$$

such that $\boldsymbol{H}$ is

$$\boldsymbol{H} = [-\boldsymbol{\varepsilon}\ \ \eta\boldsymbol{I}_3 - \boldsymbol{S}(\boldsymbol{\varepsilon})] \in \mathbb{R}^{3\times 4} \tag{5}$$

where $\boldsymbol{S}(\boldsymbol{\varepsilon})$ is the skew-symmetric matrix such that $\boldsymbol{S}(\boldsymbol{\lambda})^T = -\boldsymbol{S}(\boldsymbol{\lambda})$ and it is defined as

$$\boldsymbol{S}(\boldsymbol{\lambda}) = \begin{bmatrix} 0 & -\lambda_3 & \lambda_2 \\ \lambda_3 & 0 & -\lambda_1 \\ -\lambda_2 & \lambda_1 & 0 \end{bmatrix} \tag{6}$$

To account for the environmental disturbances the model will be formulated in relative velocity $\boldsymbol{\nu}_r$.

$$\boldsymbol{\nu}_r = \boldsymbol{\nu} - \boldsymbol{\nu}_c \tag{7}$$

where $\boldsymbol{\nu}_c$ is the velocity of the water current in the body-fixed frame.

Assumption 1. The current is constant and irrotational in the inertial frame.

Remark 1. Assumption 1 is reasonable in the sense that both amplitude and direction of currents are slowly varying.

Assumption 2. The fluid is viscid, incompressible and irrotational.

Remark 2. Assumption 2 is common in hydrodynamic modelling.

Assumption 3. The cross-flow can be neglected in control applications.

Remark 3. Assumption 3 is not strictly true, however for the purpose of control oriented modelling, the assumption is acceptable.

The kinetic model for marine systems in relative velocity was derived in Fossen (2011) and is shown below

$$\boldsymbol{M}\dot{\boldsymbol{\nu}}_r + \boldsymbol{D}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \boldsymbol{C}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \boldsymbol{g}(\boldsymbol{\eta}) = \boldsymbol{\tau} \tag{8}$$

The model in Eq. (8) form the local model of a combined system. This leads to Section 3, where the general problem of constrained dynamics are presented.

3. CONSTRAINED DYNAMICS

The challenge of constrained dynamics is to ensure physically sound motion of a system where the states are not independent due to imposed constraints. Different approaches exist for solving the constraining forces and thereby the resulting motion of the constrained system. For reconfigurable robots, cyclic configurations can cause redundant constraints to appear and, as a result, the constraint matrix will no longer be full rank. When this occurs, classical modelling methods will fail as they cannot provide a unique solution for the constrained forces. The Udwadia-Kalaba methodology, in contrast, does not require a constraint matrix to be full rank. This section discusses the issues related to modelling of constrained dynamics.

Consider the generalised Newtonian system $\mathcal{G}$

$$\mathcal{G} := \begin{cases} \dot{\boldsymbol{q}} = \boldsymbol{v} \\ \boldsymbol{M}\dot{\boldsymbol{v}} = \boldsymbol{Q} \end{cases} \tag{9}$$

where $\boldsymbol{q} \in \mathbb{R}^{n_q}$ is the vector of generalised coordinates, $\boldsymbol{M} \in \mathbb{R}^{n_q \times n_q}$ is the system inertia matrix and $\boldsymbol{Q} \in \mathbb{R}^{n_q}$ is a vector of generalised forces.

Constraints emerge in such system as a consequence of physical restrictions. A system described by ordinary differential equations (ODE) and with constraints forms a differential-algebraic equation (DAE) system. Such DAE systems are difficult to solve, and are not easily used as basis for control design. The aim of modelling is to get a system description that takes an ODE form.

If constraints appear in *holonomic* form, see definition below, they can be eliminated by coordinate reduction, that, however, results in high complexity descriptions.

Definition 1. A constraint c is said to be *holonomic* iff it can be represented independently of the generalised velocities $\dot{\boldsymbol{q}}$ such as in the following equation

$$c(\boldsymbol{q}, t) = 0 \tag{10}$$

From a geometric point-of-view the motion of the dynamical system of Eq. (9) would evolve on the sub-manifold $\mathcal{M}$ defined as

$$\mathcal{M} = \{(\boldsymbol{q}, \boldsymbol{v}) : c(\boldsymbol{q}) = 0,\ \nabla_q c(\boldsymbol{q})\boldsymbol{v} = 0\} \tag{11}$$

The motion on the manifold is constrained by $\nabla_q c(\boldsymbol{q})\boldsymbol{v} = 0$ which is often called a *hidden constraint*, since it does not